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PREPARATION AND PROPERTIES OF THE SYSTEMS  
 $Fe(2-x)Cr(x)WO_6$   $Fe(2-x)Rh(x)WO_6$ ..(U) BROWN UNIV  
 PROVIDENCE RI DEPT OF CHEMISTRY M LEIVA ET AL.  
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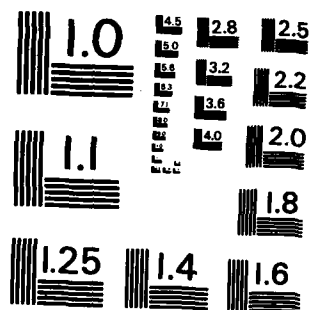
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tri- $\alpha$ - $\text{PbO}_2$  structure and is antiferromagnetic and conducting. The random rutile  $\text{Rh}_2\text{WO}_6$  is conducting, and the difference between its magnetic and electric properties and those of the inverse trirutile  $\text{Cr}_2\text{WO}_6$  are discussed in terms of possible interactions between  $\text{Cr}^{3+}(3d)$  or  $\text{Rh}^{3+}(4d)$  orbitals and  $\text{W}^{6+}(5d)$  orbitals.

(6+)

(3+)

(3+)

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TECHNICAL REPORT NO. 24

Preparation and Properties of the Systems  
 $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$ ,  $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$ , and  $\text{Cr}_{2-x}\text{Rh}_x\text{WO}_6$

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## INTRODUCTION

It has been reported (1-3) that  $\text{Fe}_2\text{WO}_6$  crystallizes with the tri- $\alpha$ - $\text{PbO}_2$  structure when prepared at temperatures above  $800^\circ\text{C}$ . This phase shows high conductivity as a result of the formation of a small amount of  $\text{FeWO}_4$  and its solid solution in  $\text{Fe}_2\text{WO}_6$  (3). The existence of both  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  is assumed to be the basis for the observed conductivity.

$\text{Cr}_2\text{WO}_6$  and  $\text{Rh}_2\text{WO}_6$  crystallize with the trirutile and the rutile structures, respectively. The magnetic structure of  $\text{Cr}_2\text{WO}_6$  derived from neutron diffraction data (4,5) shows antiferromagnetic behavior with a Néel temperature at  $69^\circ\text{K}$ . However, bulk susceptibility measurements at elevated temperatures have not been made. In addition, there has been no report concerning the electronic properties of this phase.  $\text{Rh}_2\text{WO}_6$  was first prepared by Badaud and Omaly (6). The structure assignment was based on analysis of x-ray diffraction patterns from polycrystalline samples as well as infrared spectra studies. There have been no reported studies of either the magnetic or electronic properties of  $\text{Rh}_2\text{WO}_6$ .

In both the random rutile and trirutile structures, there is edge sharing of  $\text{MO}_6$  octahedral units in such a way that straight chains are formed parallel to the c-direction. Separate chains are linked together by means of corner sharing. For both  $\text{Cr}_2\text{WO}_6$  and  $\text{Rh}_2\text{WO}_6$ , these chains contain tungsten and either chromium or rhodium ions. It was the main purpose of this study to measure the crystallographic, magnetic, and electronic properties of these compounds in order to determine if there was an significant interaction between  $\text{Cr}^{3+}(3d)$

or  $\text{Rh}^{3+}(4d)$  orbitals and  $\text{W}^{6+}(5d)$  orbitals. Such interactions, if present, might allow some delocalization of the d-electrons to take place, resulting in conducting materials. Solid solutions of the end members  $\text{Fe}_2\text{WO}_6$ ,  $\text{Cr}_2\text{WO}_6$ , and  $\text{Rh}_2\text{WO}_6$  were prepared, and their crystallographic and magnetic properties were determined.

#### EXPERIMENTAL

All materials in the systems  $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$ ,  $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$ , and  $\text{Cr}_{2-x}\text{Rh}_x\text{WO}_6$  were prepared from the solid state reactions of the reactants:  $\text{Fe}_2\text{O}_3$  (Mapico Red);  $\text{Cr}_2\text{O}_3$ , which was obtained by the decomposition in air of ammonium dichromate (Mallinkrodt, analytical reagent) for 36 h at  $600^\circ\text{C}$ ;  $\text{WO}_3$ , which was prepared by heating 99.9% tungsten foil (Schwarzkopf Dev. Co.) under flowing oxygen for 80 h at  $1000^\circ\text{C}$ ; and  $\text{Rh}_2\text{O}_3$ , which was obtained by heating rhodium metal at  $800^\circ\text{C}$  under flowing oxygen until constant weight was obtained. A finely ground mixture of stoichiometric amounts of the starting materials was placed either in a covered platinum crucible (system  $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$ ) or in a silica tube (systems  $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$  and  $\text{Cr}_{2-x}\text{Rh}_x\text{WO}_6$ ) and heated in air at the temperature and time indicated in Table I. Each sample was x-rayed, reground, and then reheated. This process was repeated until x-ray diffraction patterns of the products indicated the formation of a single phase. A Philips-Norelco diffractometer with  $\text{CuK}\alpha_1$  radiation ( $\lambda=1.5405\text{\AA}$ ) was used at a scan rate of  $0.25^\circ/2\theta/\text{min}$  and a chart speed 30 in/h. Cell parameters were obtained from a least-squares refinement of the data with the aid of a computer.

Sintered discs of  $\text{Fe}_2\text{WO}_6$  were prepared as described previously (3). Sintered discs of  $\text{Cr}_2\text{WO}_6$  were formed by pressing aliquots of 200 mg at 90,000 psi; 10 drops of Carbowax were added to the powder before pressing in order to facilitate the formation of a well-sintered disc. The pressed discs were placed on a bed of powder having the same composition in an alumina crucible, were heated at a rate of  $50^\circ\text{C}/\text{h}$  to  $975^\circ\text{C}$ , and were maintained at that temperature for 36 h. At the end of the sintering process, the discs were cooled at the same rate. They were x-rayed with  $\text{CuK}\alpha_1$  radiation and their x-ray diffraction patterns were compared to those of polycrystalline  $\text{Cr}_2\text{WO}_6$  to confirm that the phase did not undergo any changes during the sintering process. Similarly, sintered discs of  $\text{Rh}_2\text{WO}_6$  were formed by pressing aliquots of 200 mg at 90,000 psi. The pressed discs were placed on a bed of polycrystalline  $\text{Rh}_2\text{WO}_6$  in an opened silica tube. The discs were heated at a rate of  $50^\circ\text{C}/\text{h}$  to  $975^\circ\text{C}$  and were maintained at that temperature for 36 h. At the end of the process, the discs were cooled at the same rate and were x-rayed with  $\text{CuK}\alpha_1$  radiation, as described for  $\text{Cr}_2\text{WO}_6$ .

Magnetic susceptibilities were measured using a Faraday balance (7,8) at a field strength of 10.4 kOe. Honda-Owens (field dependency) plots were also made to determine the presence or absence of ferromagnetic impurities. The data were then corrected for core diamagnetism (9). When observed, Néel temperatures ( $T_N$ ) were estimated from the minima of the plots of inverse molar magnetic susceptibility versus temperature.

The electrical resistivities were measured using the van der Pauw technique (10). Contacts were made by the ultrasonic soldering of indium



directly onto the samples, and their ohmic behaviors were established by measuring their current-voltage characteristics. The Seebeck coefficient was obtained by applying a temperature gradient to a disc and recording the resulting voltage difference. The sign of this coefficient was used to determine the sign of the majority carriers.

## RESULTS AND DISCUSSION

### Structure and Crystallography

$\text{Fe}_2\text{WO}_6$  has been reported to crystallize with the columbite structure when prepared below  $800^\circ\text{C}$  (11) and with the tri- $\alpha$ - $\text{PbO}_2$  structure when prepared at a higher temperature (1-3). Both of these structures have been discussed previously (12) and may be regarded as superlattice variants of  $\alpha$ - $\text{PbO}_2$ . In this study, the tri- $\alpha$ - $\text{PbO}_2$  phase was prepared and characterized. This structure consists of hcp planes of oxygen anions in which only half of the octahedral sites are occupied by the metal atoms, Fe or W. As shown in Figure 1, each of the resulting octahedra shares a pair of skew edges in such a way that zigzag chains are formed parallel to the c-direction. The separate chains are linked to each other by means of corner sharing. Senegas and Galy (2) have indicated that in the tri- $\alpha$ - $\text{PbO}_2$  form of  $\text{Fe}_2\text{WO}_6$  one third of the zigzag chains contain only iron atoms, and two thirds of the chains show a 1:1 ordering of iron and tungsten atoms. The 2:1 cation order results in a tripling of the b-parameter.  $\text{Fe}_2\text{WO}_6$  crystallizing with the tri- $\alpha$ - $\text{PbO}_2$  structure is orthorhombic (space group Pbcn) with the following cell constants:  $a=4.577(4)\text{\AA}$ ,  $b=16.75(4)\text{\AA}$ ,  $c=4.965(4)\text{\AA}$

The crystallographic structure of  $\text{Cr}_2\text{WO}_6$  has been described by Bayer (13). The compound crystallizes with the "inverse trirutile structure," which may be regarded as a superlattice variant of the fundamental rutile structure. It consists of an hexagonal close-packed array of oxygen anions in which one half of the octahedral interstices are occupied by the metal atoms, Cr or W, in a regular 2:1 distribution. The structure is shown in Figure 2. Each of the resulting octahedra shares a pair of opposite edges in such a way that straight chains are formed parallel to the c-direction. Separate chains are corner linked to each other. Within these chains, a 2:1 cation order results in a tripling of the c-parameters.  $\text{Cr}_2\text{WO}_6$  is tetragonal (space group  $\text{P4}_2/\text{mmn}$ ) with  $a=4.580(4)\text{\AA}$  and  $c=8.865(4)\text{\AA}$ .

The existence of  $\text{Rh}_2\text{WO}_6$  has been first reported by Badaud and Omaly (6).  $\text{Rh}_2\text{WO}_6$  crystallizes with the rutile structure, in which the Rh and W atoms are statistically distributed in the lattice.  $\text{Rh}_2\text{WO}_6$  is tetragonal (space group  $\text{P4}_2/\text{mmn}$ , with  $a=4.608(4)\text{\AA}$  and  $c=3.033(4)\text{\AA}$ .

The crystallographic cell parameters obtained for  $\text{Fe}_2\text{WO}_6$ ,  $\text{Cr}_2\text{WO}_6$ , and  $\text{Rh}_2\text{WO}_6$  are in close agreement with those reported previously (2-6,14). The precise cell parameters obtained for some members of the systems  $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$ ,  $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$ , and  $\text{Cr}_{2-x}\text{WO}_6$  are indicated in Table II. Chromium cannot be substituted into the tri- $\alpha$ - $\text{PbO}_2$  structure, but the system  $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$  does form a solid solution crystallizing with the trirutile structure over a composition range of  $2 \geq x \geq 0.3$ . The decrease in cell volume with increasing chromium content follows Végard's law and is consistent with the difference in the ionic radii of  $\text{Fe}^{3+}$  (0.65 $\text{\AA}$ ) and  $\text{Cr}^{3+}$  (0.615 $\text{\AA}$ ) (15). Similarly for the system  $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$ , rhodium cannot be substituted into the tri- $\alpha$ - $\text{PbO}_2$  phase, but a solid solution does form with the trirutile structure over the range  $2 \geq x \geq 0.3$ . The slight change in the cell volume with composition is consis-

tent with the similarity between the ionic radii of  $\text{Fe}^{3+}$  ( $0.65\text{\AA}$ ) and  $\text{Rh}^{3+}$  ( $0.665\text{\AA}$ ) (15). In the system  $\text{Cr}_{2-x}\text{Rh}_x\text{WO}_6$ , there are two compositional ranges crystallizing with the trirutile structure: the range  $0.4 \leq x \leq 0$  represents the solubility of rhodium in  $\text{Cr}_2\text{WO}_6$ ; the range  $2 \geq x \geq 1.7$  may be regarded as representing the solubility of Cr atoms in  $\text{Rh}_2\text{WO}_6$ . In the range  $1.7 > x \geq 0.4$ , two trirutile phases are observed to be present. The increase of the cell volume with increasing rhodium content is consistent with the difference between the ionic radii of  $\text{Cr}^{3+}$  and  $\text{Rh}^{3+}$ .

#### Magnetic Properties

The magnetic structure of  $\text{Fe}_2\text{WO}_6$  was determined by means of neutron diffraction by Pinto et al. (16); they reported antiferromagnetic ordering at 4.2K with a Néel temperature of approximately 240K. They confirmed the existence of antiferromagnetic ordering by measuring the magnetic susceptibility from 80 to 298K. In this present study, high temperature susceptibility measurements indicate that the inverse magnetic susceptibility varies linearly with temperature above 600K. The susceptibility data obtained between 298 and 800K are shown in Figure 3; a Weiss constant of approximately -450K and an effective molar Curie constant of 7.7 ( $\text{emu-mole}^{-1}\text{K}$ ) were determined. The latter value corresponds to a spin-only moment of about  $5.6\mu_B$ , which is in agreement with the spin-only value of  $5.9\mu_B$  for  $\text{Fe}^{3+}$  ( $S=5/2$ ). Between 300K and 600K, the temperature dependency of the inverse magnetic susceptibility is not linear because of the presence of some short-range magnetic order.

The magnetic structure of  $\text{Cr}_2\text{WO}_6$  has been determined previously by Montmory (4) and Kunnmann (5). It was found from both neutron diffraction and bulk susceptibility measurements that  $\text{Cr}_2\text{WO}_6$  is ordered antiferromagnetically at 4.2K, with a Néel temperature of 69K (4) and a Weiss constant of -196K. In this present study, high-temperature susceptibility measurements were made between 298 and 800K. Above 300K, there is a linear dependency of the inverse magnetic susceptibility on temperature. A Curie constant of 3.7 gives a calculated magnetic moment of  $3.9\mu_B$  which agrees with the spin-only value of  $3.87\mu_B$  for  $\text{Cr}^{3+}$  ( $S=3/2$ ).

The molar magnetic susceptibility of  $\text{Rh}_2\text{WO}_6$  is  $3.8 \times 10^{-4}$  (emu/mole) at 298K and shows a small temperature dependency in the range from 77 to 298K ( $\chi_{77K} \sim 2[\chi_{298}]$ ). This result suggests the existence of a small number of unpaired electrons which may arise from the presence of trace amounts of  $\text{Rh}^{4+}$  ( $3d^5$ ) in the sample.

The magnetic data for the system  $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$  are summarized in Table III. All compositions in this system show a Curie-Weiss behavior above room temperature. The effective molar Curie constants,  $C_M$ , agree with those values expected from the contributions of the spin-only moments of high-spin  $\text{Fe}^{3+}$  and  $\text{Cr}^{3+}$ . Below room temperature, all members order antiferromagnetically, as indicated by negative values of the Weiss constant,  $\theta$ , and by the presence of distinct Néel temperatures in the inverse susceptibility-versus-temperature plots. Figure 4 shows the inverse magnetic susceptibility versus temperature for the compositions  $\text{Fe}_{1.7}\text{Cr}_{0.3}\text{WO}_6$ . From similar plots,  $T_N$  and  $\theta$  values were calculated for the other members

of the system. The strength of the antiferromagnetic interactions in the iron-containing members of the system increases with increasing iron content. This is seen from the values of  $\theta$  and  $T_N$  indicated in Table III. The increase in the strength of the antiferromagnetic interaction is related to the availability of half-filled  $\text{Fe}^{3+}(3d^5) e_g$  orbitals. (17)

The magnetic data for the systems  $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$  and  $\text{Cr}_{2-x}\text{Rh}_x\text{WO}_6$  are so summarized in Table III. Members of both systems show Curie-Weiss behavior, with effective molar Curie constants corresponding closely to those calculated from contributions from the spin-only moments of either high-spin  $\text{Fe}^{3+}(3d^5)$  or  $\text{Cr}^{3+}(3d^3)$  and diamagnetic low-spin  $\text{Rh}^{3+}(3d^6)$ . All compounds indicate the presence of antiferromagnetic interactions as indicated by the negative  $\theta$  values. The decrease of the magnitude of  $\theta$  upon rhodium substitution is consistent with the weakening of these interactions by the presence of diamagnetic  $\text{Rh}^{3+}$  ions. The magnetic susceptibility data for the composition  $\text{Fe}_{1.6}\text{Rh}_{0.4}\text{WO}_6$  is shown in Figure 5; there are sufficient antiferromagnetic interactions present so that the Néel temperature is clearly observed.

### Electrical Properties

The electrical properties of  $\text{Fe}_2\text{WO}_6$  have been determined previously (3).  $\text{Fe}_2\text{WO}_6$  is an n-type semiconductor with an activation energy of 0.17(1) eV and a room temperature resistivity of  $\sim 50(\Omega\text{-cm})$ . This extrinsic semiconducting behavior is consistent with the existence of a solid solution of small amounts of  $\text{FeWO}_4$  in  $\text{Fe}_2\text{WO}_6$ , thereby introducing iron(II) and iron(III)

on equivalent sites; conduction may therefore occur by electron transfer along the chains containing pure iron in the tri- $\alpha$ - $\text{PbO}_2$  structure.

$\text{Cr}_2\text{WO}_6$  was found to be non-conducting ( $\rho_{298\text{K}} \sim 2 \times 10^6 \Omega\text{-cm}$ ). This result is consistent with the presence of both  $\text{Cr}^{3+}$  and  $\text{W}^{6+}$  ions in all the chains of the trirutile structure.

$\text{Rh}_2\text{WO}_6$  was found to be conducting ( $\rho = 22 \Omega\text{-cm}$  at room temperature and the conductivity is almost temperature independent. In addition, a small Seebeck coefficient was measured, which is also indicative of metallic behavior. The sign of this coefficient indicates p-type conductivity, which is consistent with the existence of  $\text{Rh}^{4+}$  as an impurity. The electrical conductivity observed in  $\text{Rh}_2\text{WO}_6$  may be a result of  $\text{Rh}(4d)\text{-W}(5d)$  interactions which make some electron transfer possible in the "disordered" rutile structure. In  $\text{Cr}_2\text{WO}_6$ ,  $\text{Cr}(3d)\text{-W}(5d)$  interactions do not occur, and hence a high resistivity is observed. Some delocalization of electrons is possible in  $\text{Rh}_2\text{WO}_6$  because of overlap of  $\text{Rh}(4d)$  orbitals with  $\text{W}(5d)$  orbitals. This observation is also consistent with the magnetic behavior observed in  $\text{Rh}_2\text{WO}_6$ .

#### CONCLUSIONS

$\text{Fe}_2\text{WO}_6$ ,  $\text{Cr}_2\text{WO}_6$ , and  $\text{Rh}_2\text{WO}_6$  have been prepared, and crystallize with the tri- $\alpha$ - $\text{PbO}_2$ , trirutile, and rutile structures, respectively.  $\text{Fe}_2\text{WO}_6$  is conducting as a result of the formation of a small amount of  $\text{FeWO}_4$  and its solid solution in  $\text{Fe}_2\text{WO}_6$ . When  $\text{Fe}_2\text{WO}_6$  crystallizes in the tri- $\alpha$ - $\text{PbO}_2$

structure, zigzag chains are formed by the linking of  $\text{FeO}_6$  octahedra, and along them, electron transfer from  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$  may give rise to conductivity. Measurements above 600K of the magnetic susceptibility of  $\text{Fe}_2\text{WO}_6$  yield an effective molar Curie constant whose value corresponds closely to that expected for spin-only  $\text{Fe}^{3+}$  ions. In addition, the large, negative Weiss constant indicates the existence of strong antiferromagnetic interactions.

$\text{Cr}_2\text{WO}_6$  crystallizes with the trirutile structure which is characterized by both tungsten and chromium ions being located in  $\text{MO}_6$  octahedra which are linked together to form straight chains. Measurements of the magnetic susceptibility of  $\text{Cr}_2\text{WO}_6$  above 300K yield an effective molar Curie constant whose value corresponds to that expected for spin-only  $\text{Cr}^{3+}$ .

$\text{Rh}_2\text{WO}_6$  also crystallizes in the random rutile structure, and shows small temperature dependencies in its magnetic susceptibility and its electrical conductivity. The Seebeck coefficient indicates p-type conduction. This behavior of  $\text{Rh}_2\text{WO}_6$  is consistent with the presence of  $\text{Rh}^{4+}$  as an impurity and with the existence of interactions between Rh(4d) orbitals and W(5d) orbitals in the rutile structure.

Solid solutions of the end members  $\text{Fe}_2\text{WO}_6$ ,  $\text{Cr}_2\text{WO}_6$ , and  $\text{Rh}_2\text{WO}_6$  can be prepared, and crystallize with the trirutile structure over different compositional ranges. Magnetic susceptibility measurements for all the resulting solid solutions yield effective molar Curie constants corresponding closely to those calculated from the contributions of the spin-only

moments of high-spin  $\text{Fe}^{3+}$ ,  $\text{Cr}^{3+}$  and diamagnetic low-spin  $\text{Rh}^{3+}$  ions. In addition, negative Weiss constants indicate the existence of antiferromagnetic interactions in these compounds.

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TABLE I  
Reaction Conditions for the Synthesis  
of Single Phase Compounds

<u>Nominal Composition</u>	<u>Reaction Temperature/Time</u>
$\text{Fe}_2\text{WO}_6$	950°C/5 days
$\text{Fe}_{1.7}\text{Cr}_{0.3}\text{WO}_6$	950°C/6 days
$\text{Fe}_{1.5}\text{Cr}_{0.5}\text{WO}_6$	950°C/4 days
$\text{FeCrWO}_6$	950°C/4 days
$\text{Cr}_2\text{WO}_6$	950°C/6 days
$\text{Fe}_2\text{WO}_6$	950°C/5 days
$\text{Fe}_{1.6}\text{Rh}_{0.4}\text{WO}_6$	900°C/1.5 days, 950°C/2 days
$\text{FeRhWO}_6$	850°C/3 days, 900°C/1.5 days
$\text{Fe}_{0.8}\text{Rh}_{1.2}\text{WO}_6$	850°C/9 days
$\text{Fe}_{0.6}\text{Rh}_{1.4}\text{WO}_6$	850°C/12 days
$\text{Fe}_{0.3}\text{Rh}_{1.7}\text{WO}_6$	850°C/3.5 days, 875°C/14.5 days
$\text{Rh}_2\text{WO}_6$	850°C/3.5 days, 875°C/16 days, 900°C/2 days, 930°C/2 days
$\text{Cr}_2\text{WO}_6$	950°C/6 days
$\text{Cr}_{1.8}\text{Rh}_{0.2}\text{WO}_6$	850°C/2.5 days, 900°C/2 days, 950°C/1.5 days
$\text{Cr}_{1.6}\text{Rh}_{0.4}\text{WO}_6$	900°C/6 days, 950°C/2 days
$\text{Rh}_2\text{WO}_6$	850°C/3.5 days, 875°C/16 days, 900°C/2 days, 930°C/2 days

Table II  
CRYSTALLOGRAPHIC PROPERTIES

System $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$						
Compound	a(Å)	b(Å)	c(Å)	V(Å) <sup>3</sup>	Structure	Space Group
$\text{Fe}_2\text{WO}_6$	4.577(4)	16.75(4)	4.965(4)	380.6	tri- $\alpha$ - $\text{PbO}_2$	Pbcn
$\text{Fe}_{1.7}\text{Cr}_{0.3}\text{WO}_6$	4.627(4)	-	8.964(4)	192.0	trirutile	$\text{P4}_2/\text{mmn}$
$\text{Fe}_{1.5}\text{Cr}_{0.5}\text{WO}_6$	4.619(4)	-	8.941(4)	190.8	trirutile	$\text{P4}_2/\text{mmn}$
$\text{FeCrWO}_6$	4.607(4)	-	8.916(4)	189.2	trirutile	$\text{P4}_2/\text{mmn}$
$\text{CrWO}_6$	4.580(4)	-	8.865(4)	186.0	rutile	$\text{P4}_2/\text{mmn}$

System $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$						
Compound	a(Å)	b(Å)	c(Å)	V(Å) <sup>3</sup>	Structure	Space Group
$\text{Fe}_2\text{WO}_6$	4.577(4)	16.75(5)	4.965(4)	380.6	tri- $\alpha$ - $\text{PbO}_2$	Pbcn
$\text{Fe}_{1.6}\text{Rh}_{0.4}\text{WO}_6$	4.633(4)	-	8.974(4)	192.6	trirutile	$\text{P4}_2/\text{mmn}$
$\text{FeRhWO}_6$	4.631(4)	-	9.002(4)	193.1	trirutile	$\text{P4}_2/\text{mmn}$
$\text{Fe}_{0.8}\text{Rh}_{1.2}\text{WO}_6$	4.629(4)	-	9.015(4)	193.2	trirutile	$\text{P4}_2/\text{mmn}$
$\text{Fe}_{0.6}\text{Rh}_{1.4}\text{WO}_6$	4.622(4)	-	9.031(4)	192.9	trirutile	$\text{P4}_2/\text{mmn}$
$\text{Fe}_{0.3}\text{Rh}_{1.7}\text{WO}_6$	4.615(4)	-	9.062(4)	193.0	trirutile	$\text{P4}_2/\text{mmn}$
$\text{Rh}_2\text{WO}_6$	4.608(4)	-	3.033(4)	64.4(*)	rutile	$\text{P4}_2/\text{mmn}$

System $\text{Cr}_{2-x}\text{Rh}_x\text{WO}_6$						
Compound	a(Å)	c(Å)	V(Å) <sup>3</sup>	Structure	Space Group	
$\text{CrWO}_6$	4.580(4)	8.865(4)	186.0	trirutile	$\text{P4}_2/\text{mmn}$	
$\text{Cr}_{1.8}\text{Rh}_{0.2}\text{WO}_6$	4.585(4)	8.879(4)	186.7	trirutile	$\text{P4}_2/\text{mmn}$	
$\text{Cr}_{1.6}\text{Rh}_{0.4}\text{WO}_6$	4.590(4)	8.895(4)	187.4		$\text{P4}_2/\text{mmn}$	
$\text{Rh}_2\text{WO}_6$	4.608(4)	3.033(4)	64.4(*)		$\text{P4}_2/\text{mmn}$	

(\*) When indexed as a trirutile,  $\text{Rh}_2\text{WO}_6$  has a calculated cell volume of  $193.2(\text{Å})^3$

Table III  
MAGNETIC PROPERTIES  
System  $\text{Fe}_{2-x}\text{Cr}_x\text{WO}_6$

<u>Compound</u>	<u><math>1/C_M</math> Found</u>	<u><math>1/C_M</math> Expected</u>	<u><math>T_N</math>(K)</u>	<u><math>\theta</math>(K)</u>
$\text{Fe}_2\text{WO}_6$	0.13	0.12	-	$\sim$ -450
$\text{Fe}_{1.7}\text{Cr}_{0.3}\text{WO}_6$	0.11	0.12	320	-908
$\text{Fe}_{1.5}\text{Cr}_{0.5}\text{WO}_6$	0.12	0.13	276	-803
$\text{FeCrWO}_6$	0.15	0.16	236	-620
$\text{Cr}_2\text{WO}_6$	0.27	0.27	$\sim$ 80	-184

System  $\text{Fe}_{2-x}\text{Rh}_x\text{WO}_6$

<u>Compound</u>	<u><math>1/C_M</math> Found</u>	<u><math>1/C_M</math> Expected</u>	<u><math>T_N</math>(K)</u>	<u><math>\theta</math>(K)</u>
$\text{Fe}_2\text{WO}_6$	0.13	0.12	-	$\sim$ -450
$\text{Fe}_{1.6}\text{Rh}_{0.4}\text{WO}_6$	0.14	0.14	216	-625
$\text{FeRhWO}_6$	0.23	0.23	-	-387
$\text{Fe}_{0.8}\text{Rh}_{1.2}\text{WO}_6$	0.32	0.29	-	$\sim$ -295
$\text{Fe}_{0.6}\text{Rh}_{1.4}\text{WO}_6$	0.40	0.38	-	-216
$\text{Fe}_{0.3}\text{Rh}_{1.7}\text{WO}_6$	0.78	0.76	-	-102
$\text{Rh}_2\text{WO}_6$	-	-	-	-

System  $\text{Cr}_{2-x}\text{Rh}_x\text{WO}_6$

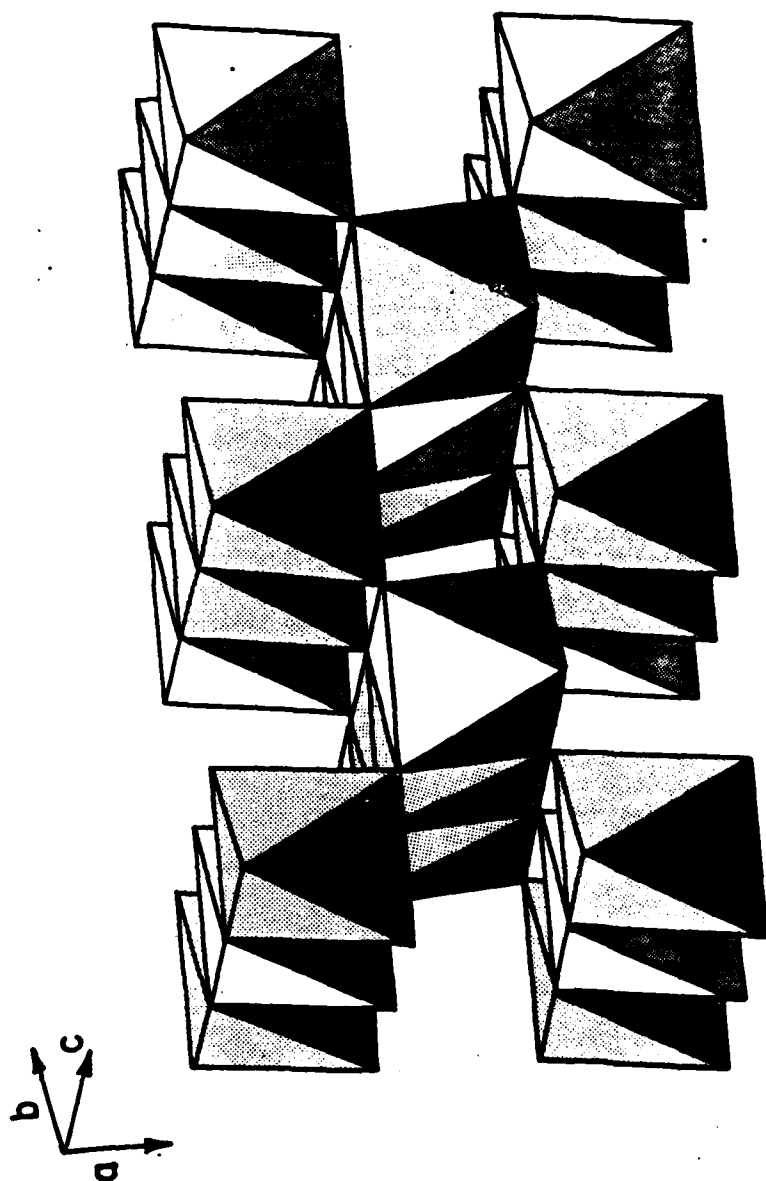
<u>Compound</u>	<u><math>1/C_M</math> Found</u>	<u><math>1/C_M</math> Expected</u>	<u><math>T_N</math>(K)</u>	<u><math>\theta</math>(K)</u>
$\text{Cr}_2\text{WO}_6$	0.27	0.27	$\sim$ 80	-184
$\text{Cr}_{1.8}\text{Rh}_{0.2}\text{WO}_6$	$\sim$ 0.28	0.30	-	$\sim$ -200
$\text{Cr}_{1.6}\text{Rh}_{0.4}\text{WO}_6$	0.32	0.33	-	-173
$\text{Rh}_2\text{WO}_6$	-	-	-	-

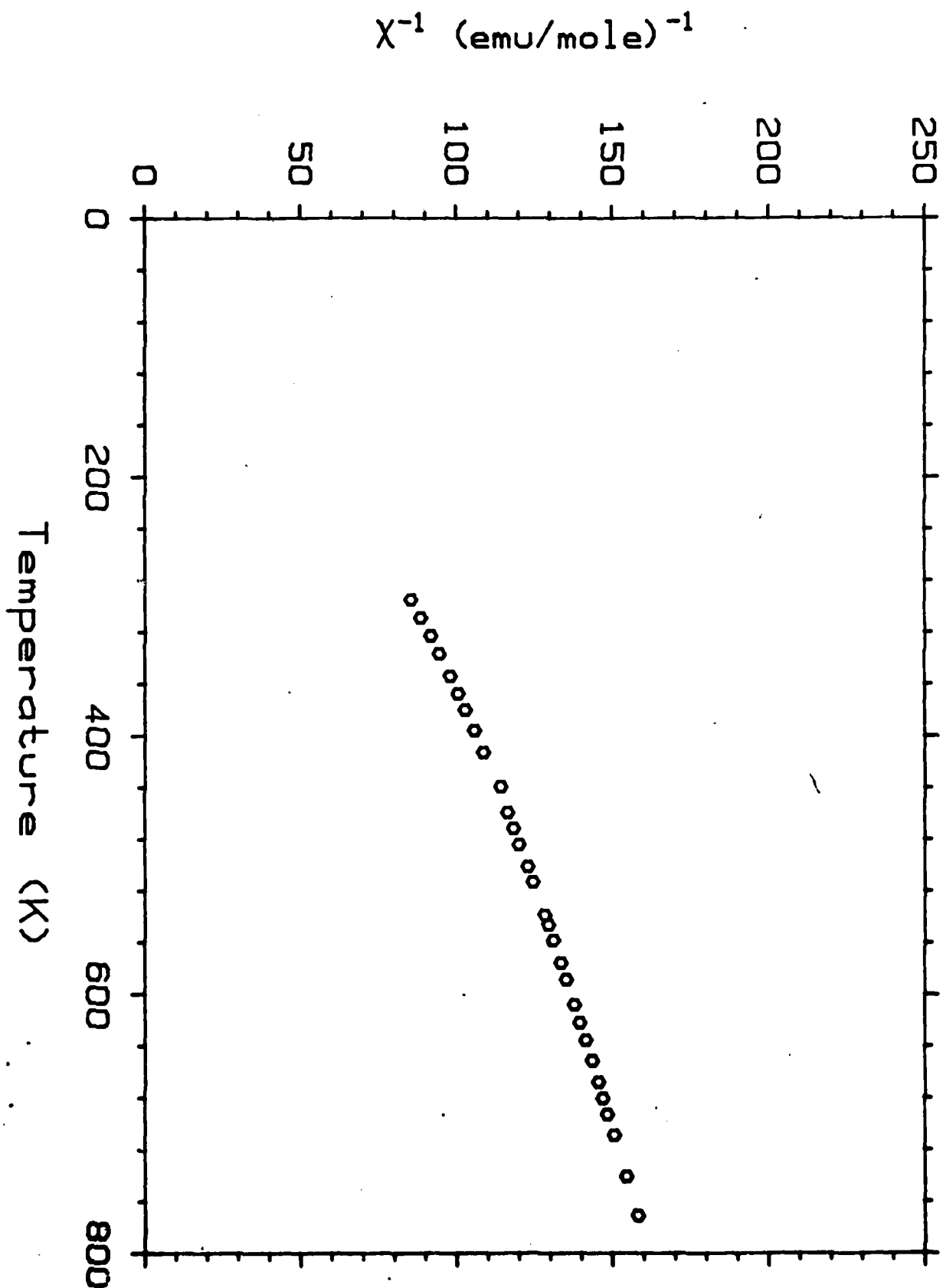
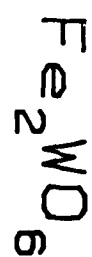
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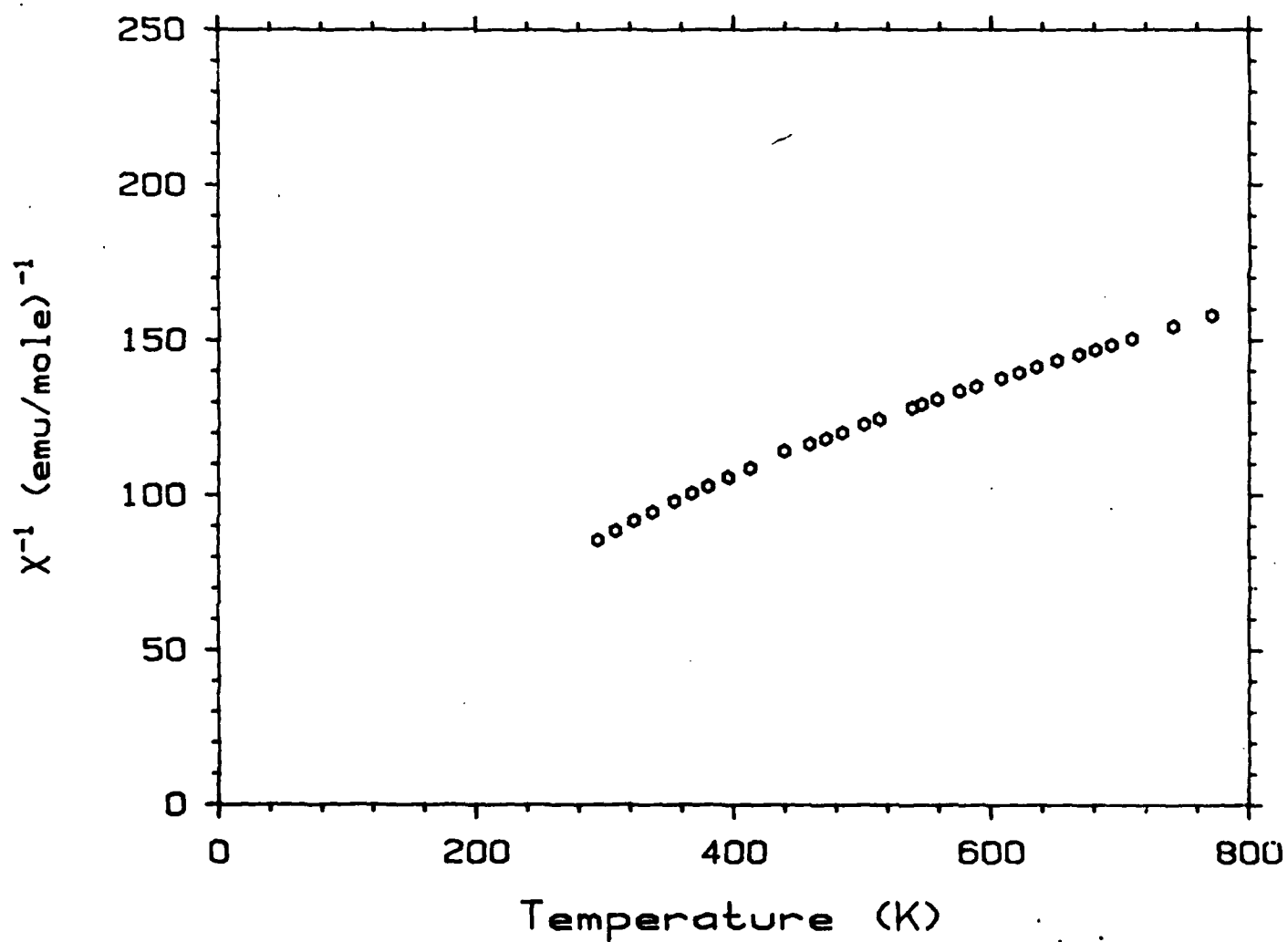
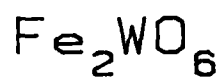
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FIGURE CAPTIONS

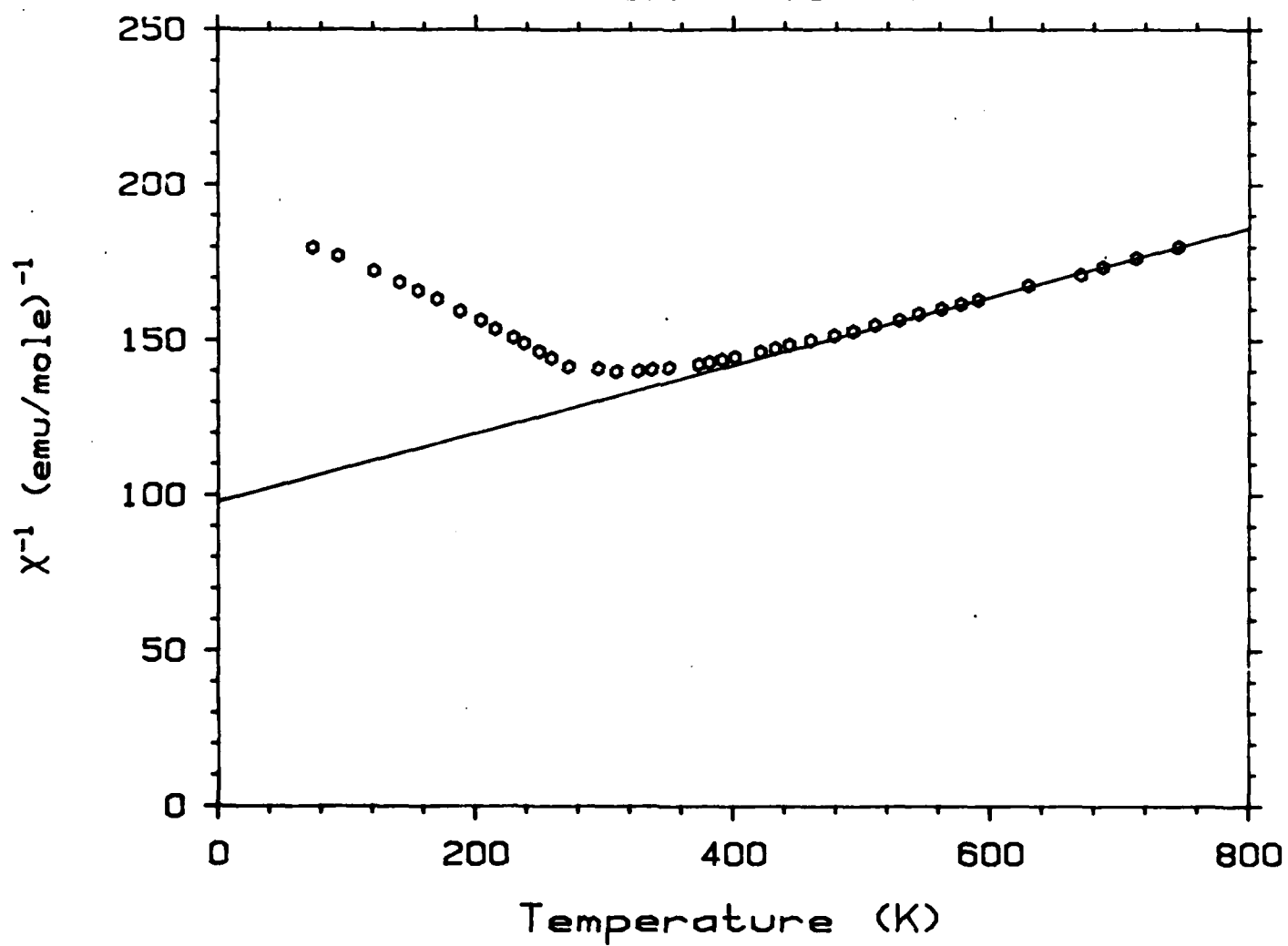
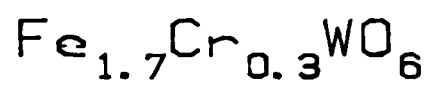
- Figure 1 - Perspective view of the tri- $\alpha$ - $\text{PbO}_2$  structure, showing skew-edge linked chains of octahedra. The lighter octahedra contain the tungsten sites.
- Figure 2 - Perspective view of the trirutile structure, showing straight chains of octahedra. The lighter octahedra contain the tungsten sites.
- Figure 3 - Temperature dependence of the inverse magnetic susceptibility of  $\text{Fe}_2\text{WO}_6$ .
- Figure 4 - Temperature dependence of the inverse magnetic susceptibility of  $\text{Fe}_{1.7}\text{Cr}_{0.3}\text{WO}_6$ .
- Figure 5 - Temperature dependence of the inverse magnetic susceptibility of  $\text{Fe}_{1.6}\text{Rh}_{0.4}\text{WO}_6$ .

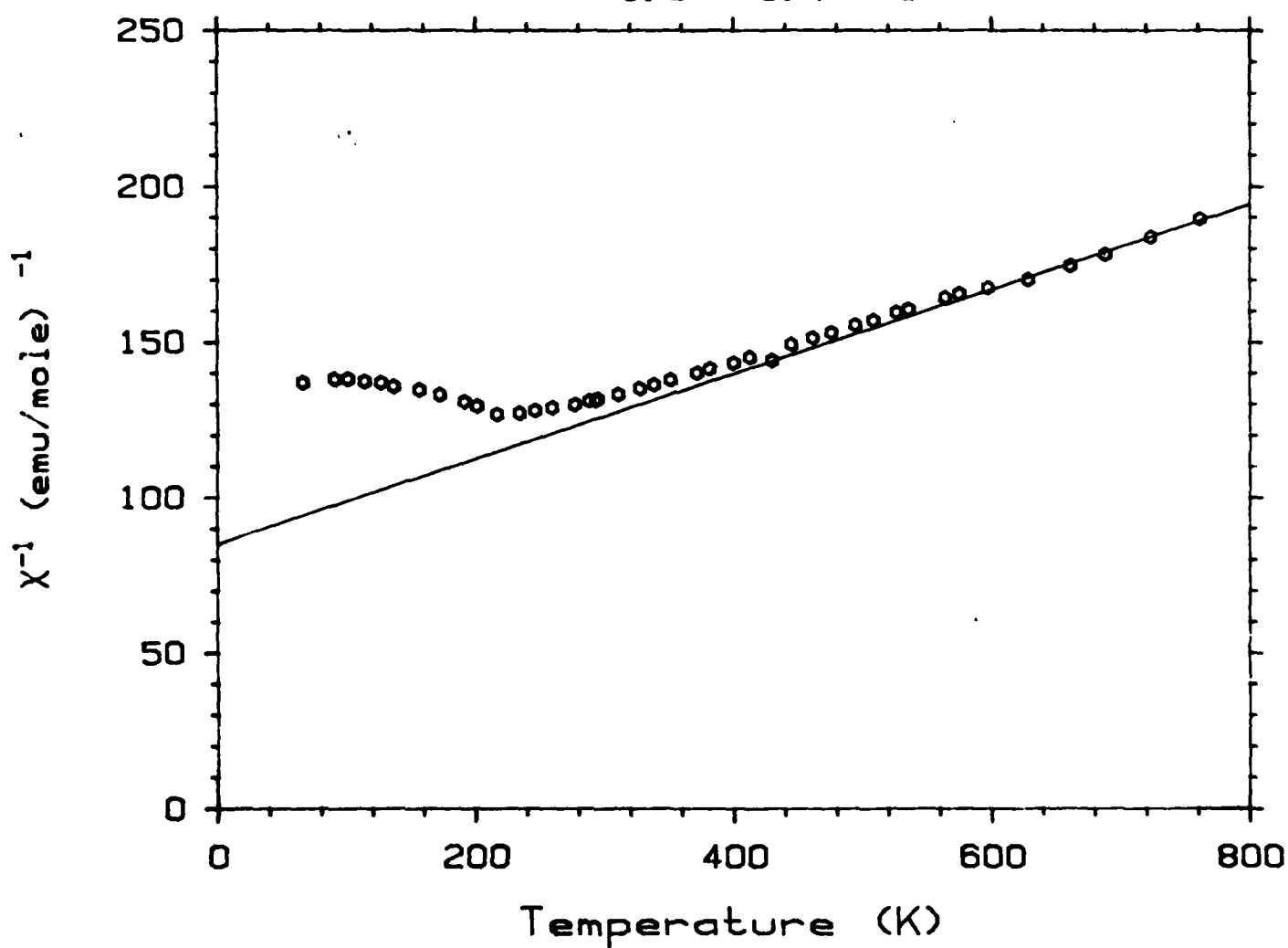












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